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(54) **METHOD FOR MANUFACTURING A STENT AND STENT MANUFACTURED THEREBY**

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(51) **Int. Cl.**

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B23K 26/38 (2014.01)
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USPC 427/2.24, 2.25; 623/1.15, 1.42, 1.46
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,153,936	A	4/1939	Owens et al.
4,531,933	A	7/1985	Norton et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP	836839	A2	10/1997
EP	1600534		11/2005

(Continued)

OTHER PUBLICATIONS

U.S. Appl. No. 09/716,146, filed Nov. 17, 2000, Boyle.

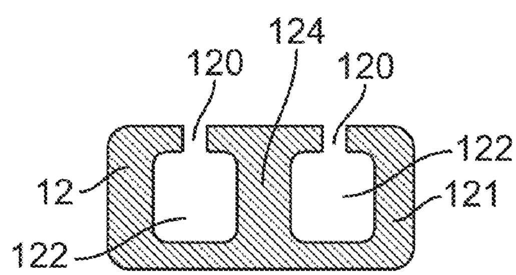
(Continued)

Primary Examiner — Cachet Sellman

(57) **ABSTRACT**

A method for manufacturing a stent includes forming a stent blank from a first material, the stent blank comprising a plurality of struts and a plurality of crowns, each crown connecting at least two struts, and a plurality of slots in at least some of the plurality of struts and/or the plurality of crowns, depositing a second material over outer surfaces of the struts and the crowns and in the slots to encase the stent blank in the second material, creating at least one opening through the second material, and removing the first material to form a stent comprising the second material, the stent having a continuous lumen from one end of the stent to the other end of the stent, the continuous lumen being partitioned in portions corresponding to the locations of the slots in the stent blank. The lumen may then be filled with a therapeutic substance.

21 Claims, 4 Drawing Sheets



(51) **Int. Cl.**
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A61F 2/915 (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,643,716 A 2/1987 Drach
4,720,384 A 1/1988 DiLuccio et al.
4,763,647 A 8/1988 Gambale
4,800,082 A 1/1989 Karbowski et al.
4,813,925 A 3/1989 Anderson, Jr. et al.
4,886,062 A 12/1989 Wiktor
4,913,683 A 4/1990 Gregory
5,019,090 A 5/1991 Pinchuk
5,063,935 A 11/1991 Gambale
5,133,732 A 7/1992 Wiktor
5,154,705 A 10/1992 Fleischhacker et al.
5,234,456 A 8/1993 Silvestrini
5,306,250 A 4/1994 March et al.
5,345,945 A 9/1994 Hodgson et al.
5,536,274 A 7/1996 Neuss
5,538,735 A 7/1996 Ahn
5,569,197 A 10/1996 Helmus et al.
5,605,162 A 2/1997 Mirzaee et al.
5,630,840 A 5/1997 Mayer
5,670,161 A 9/1997 Healy et al.
5,772,864 A * 6/1998 Møller et al. 205/73
5,782,903 A 7/1998 Wiktor
5,795,318 A 8/1998 Wang et al.
5,824,045 A 10/1998 Alt
5,843,117 A 12/1998 Alt et al.
5,882,335 A 3/1999 Leone et al.
5,891,108 A 4/1999 Leone et al.
5,902,266 A 5/1999 Leone et al.
5,957,903 A 9/1999 Mirzaee et al.
6,022,369 A 2/2000 Jacobsen et al.
6,063,101 A 5/2000 Jacobsen et al.
6,071,305 A 6/2000 Brown et al.
6,099,561 A 8/2000 Alt
6,136,023 A 10/2000 Boyle
6,248,190 B1 6/2001 Stinson
6,358,276 B1 3/2002 Edwin
6,478,778 B1 11/2002 Jacobsen et al.
6,497,709 B1 12/2002 Heath
6,558,422 B1 5/2003 Baker et al.
6,623,519 B2 9/2003 Edwin et al.
6,641,607 B1 11/2003 Hossainy et al.
6,656,162 B2 12/2003 Santini, Jr. et al.
6,699,281 B2 3/2004 Vallana et al.
6,752,829 B2 6/2004 Kocur et al.
6,783,543 B2 8/2004 Jang
6,938,668 B2 * 9/2005 Whicher et al. 164/46
6,989,071 B2 1/2006 Kocur et al.
7,037,330 B1 5/2006 Rivelli et al.
7,041,130 B2 5/2006 Santini, Jr. et al.
7,044,965 B1 5/2006 Spielberg
7,060,093 B2 6/2006 Dang et al.
7,101,392 B2 9/2006 Heath
7,122,048 B2 10/2006 Dimatteo et al.
7,135,039 B2 11/2006 De Scheerder et al.
7,182,735 B2 2/2007 Shireman et al.
7,288,084 B2 10/2007 Li
7,316,565 B2 1/2008 Liao
7,344,563 B2 3/2008 Vallana et al.
7,384,660 B2 6/2008 Hossainy et al.
7,400,931 B2 7/2008 Mandrusov et al.
7,419,681 B2 9/2008 Tormala et al.
7,455,667 B2 11/2008 Uhland et al.
7,575,593 B2 8/2009 Rea et al.
7,736,687 B2 * 6/2010 Sims et al. 427/2.1
2002/0038145 A1 * 3/2002 Jang 623/1.15
2002/0065548 A1 5/2002 Birdsall et al.
2002/0087209 A1 7/2002 Edwin et al.
2002/0103527 A1 8/2002 Kocur et al.
2002/0138048 A1 9/2002 Tuch
2003/0021825 A1 1/2003 Pathak et al.
2003/0068353 A1 4/2003 Chen et al.
2003/0125803 A1 7/2003 Vallana et al.
2003/0208256 A1 11/2003 DiMatteo et al.
2004/0006382 A1 1/2004 Sohier
2004/0024449 A1 2/2004 Boyle
2004/0037889 A1 2/2004 Richeal et al.
2004/0106984 A1 6/2004 Stinson
2004/0133270 A1 7/2004 Grandt
2004/0148012 A9 7/2004 Jang
2005/0043783 A1 2/2005 Amis et al.
2005/0060020 A1 3/2005 Jenson
2005/0070996 A1 3/2005 Dinh et al.
2005/0080481 A1 4/2005 Madda et al.
2005/0131521 A1 * 6/2005 Marton 623/1.13
2005/0145307 A1 7/2005 Shireman et al.
2005/0177226 A1 8/2005 Banik et al.
2005/0186241 A1 8/2005 Boyle et al.
2005/0208100 A1 9/2005 Weber et al.
2005/0272806 A1 12/2005 Falotico et al.
2005/0278016 A1 * 12/2005 Welsh et al. 623/1.42
2006/0004437 A1 1/2006 Jayaraman
2006/0064157 A1 3/2006 Shanley
2006/0122689 A1 6/2006 Kocur et al.
2006/0129231 A1 6/2006 De Scheerder et al.
2006/0147489 A1 7/2006 Shanley et al.
2006/0155369 A1 7/2006 Edwin et al.
2006/0212109 A1 9/2006 Sirhan et al.
2006/0224234 A1 10/2006 Jayaraman
2006/0224237 A1 10/2006 Furst et al.
2007/0005124 A1 1/2007 De Scheerder et al.
2007/0027531 A1 2/2007 Dimatteo et al.
2007/0043423 A1 2/2007 Grewe
2007/0055352 A1 3/2007 Naimark et al.
2007/0061007 A1 3/2007 Nolting
2007/0112417 A1 5/2007 Shanley et al.
2007/0123805 A1 5/2007 Shireman et al.
2007/0168021 A1 7/2007 Holmes, Jr. et al.
2007/0173923 A1 7/2007 Savage et al.
2007/0219628 A1 9/2007 Shanley et al.
2007/0282419 A1 12/2007 Hilaire et al.
2008/0003251 A1 1/2008 Zhou
2008/0051882 A1 2/2008 Rubin
2008/0065201 A1 3/2008 Li
2008/0077233 A1 3/2008 Diaz et al.
2008/0183281 A1 7/2008 Rea et al.
2008/0188925 A1 8/2008 Zhao
2008/0195170 A1 8/2008 Asgari
2008/0195196 A1 8/2008 Asgari
2008/0234809 A1 9/2008 Greenan
2008/0249599 A1 10/2008 Allen et al.
2008/0255659 A1 10/2008 Huang et al.
2008/0276935 A1 11/2008 Wang
2008/0306579 A1 12/2008 Dolan et al.
2009/0024209 A1 1/2009 Ozdil et al.
2009/0024210 A1 1/2009 Klocke et al.
2009/0035351 A1 2/2009 Berglund et al.
2009/0061071 A1 3/2009 McMorrow et al.
2009/0093871 A1 4/2009 Rea et al.
2009/0132031 A1 5/2009 Cook et al.
2009/0143855 A1 6/2009 Weber et al.
2009/0157172 A1 6/2009 Kokate et al.
2009/0163995 A1 6/2009 Shanley et al.
2009/0192593 A1 7/2009 Meyer et al.
2009/0220612 A1 9/2009 Perera
2009/0228095 A1 9/2009 Shanley et al.
2009/0281615 A1 11/2009 Kocur et al.
2009/0312833 A1 12/2009 Tittelbach et al.
2009/0319026 A1 12/2009 Meyer
2010/0010621 A1 1/2010 Klocke
2010/0023115 A1 1/2010 Robaina et al.
2010/0036482 A1 2/2010 Svrluga et al.
2010/0057196 A1 3/2010 Pathak
2010/0070022 A1 3/2010 Kuehling
2010/0082096 A1 4/2010 Gregorich
2010/0145437 A1 6/2010 Girton et al.
2011/0008405 A1 1/2011 Birdsall et al.
2011/0264187 A1 10/2011 Melder
2012/0009325 A1 * 1/2012 Storment 427/2.25
2012/0067008 A1 3/2012 Bienvenu

(56) **References Cited**

U.S. PATENT DOCUMENTS

2012/0070562	A1	3/2012	Avelar et al.	
2012/0216916	A1*	8/2012	Pacetti	A61F 2/915 141/98
2013/0284310	A1	10/2013	Peterson	
2013/0284311	A1	10/2013	Peterson	

FOREIGN PATENT DOCUMENTS

EP	836839 B1	7/2006
WO	WO94/18956	9/1994
WO	WO96/19255	6/1996
WO	WO96/26682	9/1996
WO	WO98/23228	6/1998
WO	WO00/01322	1/2000
WO	WO01/55473	8/2001
WO	WO02/060506	8/2002
WO	WO03/092547	11/2003
WO	WO2004/091686	10/2004
WO	WO2007/021749	2/2007
WO	WO2007/033282	3/2007
WO	WO2011/008896	1/2011
WO	WO2012/036929	3/2012

OTHER PUBLICATIONS

U.S. Appl. No. 12/428,581, filed Apr. 23, 2009, Hoff et al.
U.S. Appl. No. 12/500,359, filed Jul. 9, 2009, Storment et al.
U.S. Appl. No. 61/244,049, filed Sep. 20, 2009, Thompson et al.
U.S. Appl. No. 61/244,050, filed Sep. 20, 2009, Silver et al.
Basarir et al., “Osseointegration in Arthroplasty: Can Simvastatin Promote Bone Response to Implants?” International Orthopaedics (SICOT)(2009) 33:855-859.
Polacco et al. “Biodegradable Hollow Fibres Containing Drug-Loaded Nanoparticles as Controlled Release Systems” Polym International 51:1464-1472 (2002).
Derle et al., “Particle Engineering Techniques to Enhance Dissolution of Poorly Water Soluble Drugs” International Journal of Current Pharmaceutical Research, vol. 2, Issue 1, 2010, pp. 10-15.
Purvis et al., “Cryogenic Liquids, Nanoparticles, and Microencapsulation” International Journal of Pharmaceutics, 2006.
“Breakthrough Solubilization Technology Targets Stubborn Drug Candidates” Dowpharma.
“Supercritical Carbon-Dioxide Cleaning Defined” Supercritical Carbon-Dioxide Cleaning Technology Review, Jul. 1996.
Berger “Coating Drug-Eluting Arterial Stents Using Ultrasonic Spray Nozzle” ILASS Americas, 19th Annual Conference on Liquid Atomization and Spray Systems, May 2006.
Kim et al. “Electrically Controlled Hydrophobicity in a Surface Modified Nanoporous Carbon” Applied Physics Letters 98, 053106 (2011).
Vallet et al. “Electrowetting of Water and Aqueous Solutions on Poly(ethylene Terephthalate) Insulating Films” Polymer vol. 37, No. 12, pp. 2465-2470, 1996.
PCT Search Report PCT/US2014/026648.
PCT Search Report PCT/US2010/039087.
PCT Search Report PCT/US2010/049439.
PCT Search Report PCT/US2010/049437.
PCT Search Report PCT/US2010/049434.

* cited by examiner

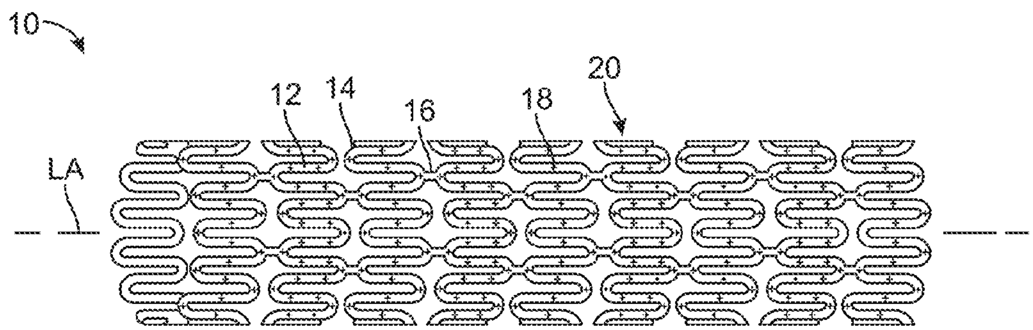

FIG. 1

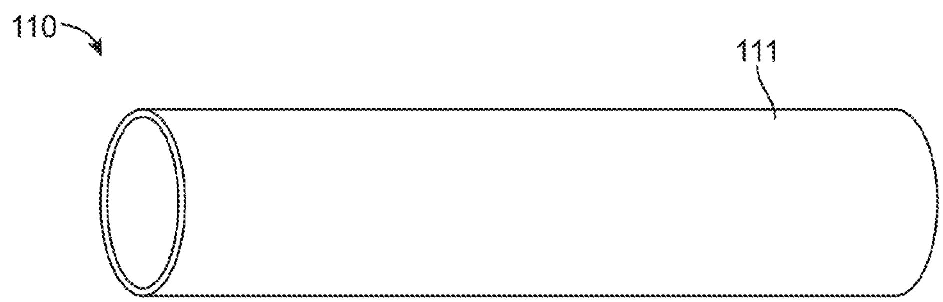

FIG. 2

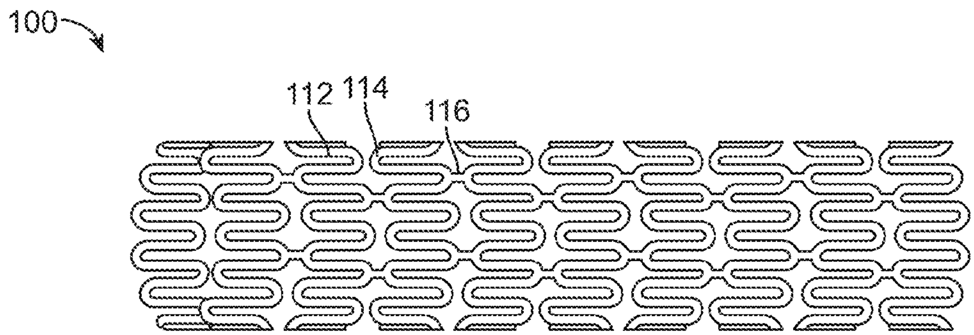

FIG. 3

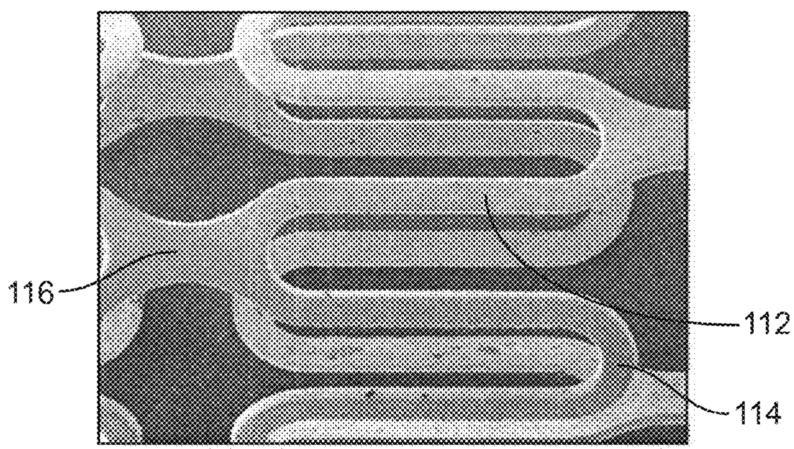

FIG. 4

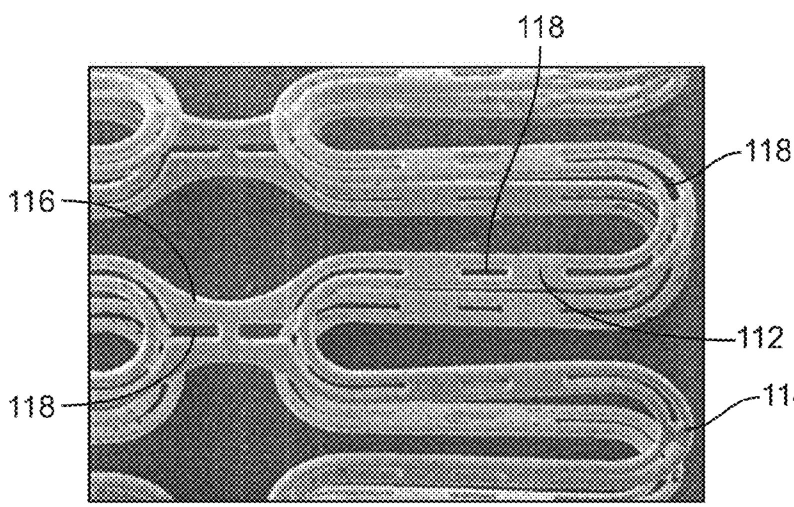

FIG. 5

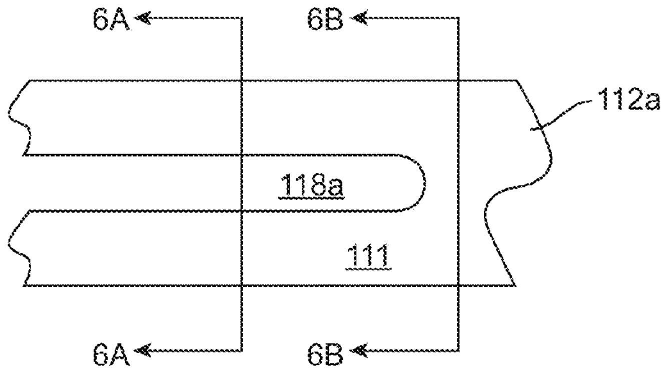

FIG. 6

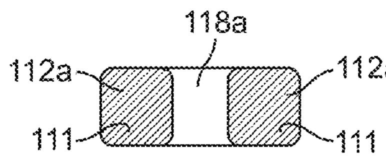

FIG. 6A

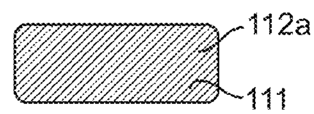

FIG. 6B

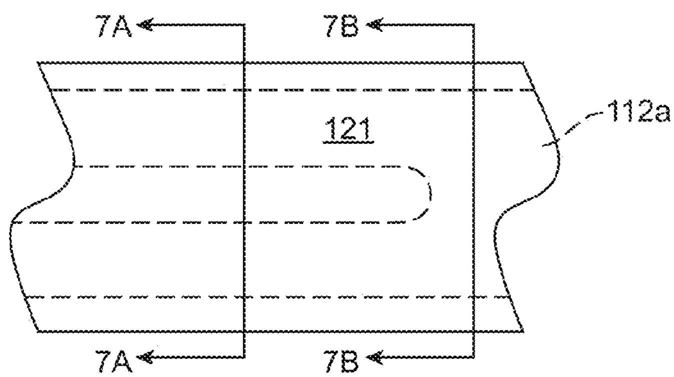

FIG. 7

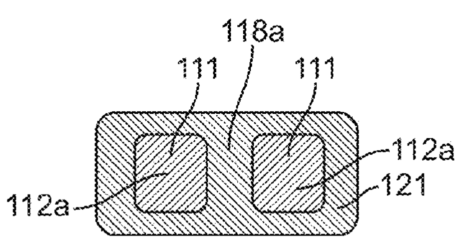

FIG. 7A

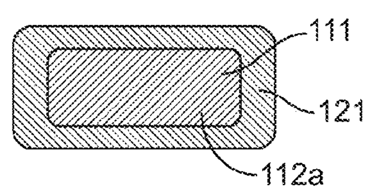

FIG. 7B

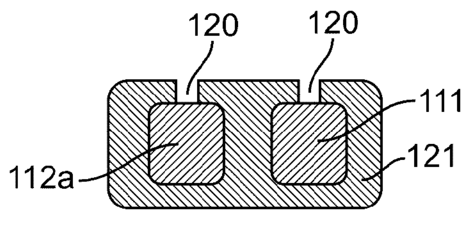

FIG. 8A

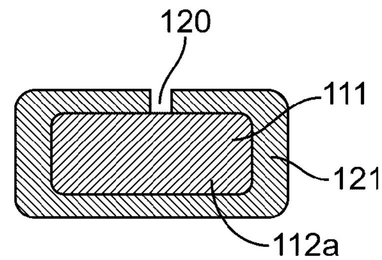

FIG. 8B

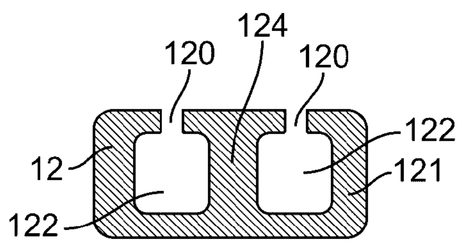

FIG. 9A

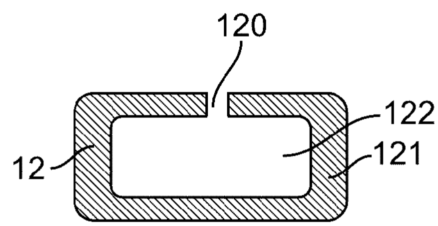

FIG. 9B

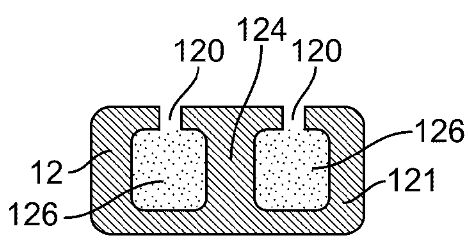

FIG. 10A

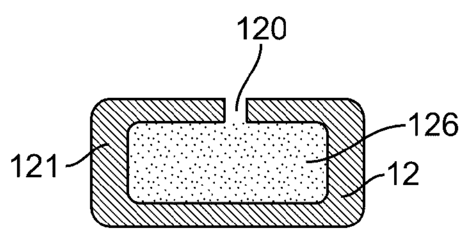

FIG. 10B

METHOD FOR MANUFACTURING A STENT AND STENT MANUFACTURED THEREBY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of priority from U.S. Provisional Patent Application No. 61/781,717, filed Mar. 14, 2013, which is incorporated herein by reference in its entirety.

FIELD

The present invention is related to a method for manufacturing a stent and a stent manufactured thereby.

BACKGROUND

Drug-eluting implantable medical devices have become popular in recent times for their ability to perform their primary function (such as structural support of a vessel, for example) and their ability to medically treat the area in which they are implanted.

For example, drug-eluting stents have been used to act as scaffolds to support lumens of vessels in open positions and to prevent restenosis in coronary arteries. Drug-eluting stents may administer therapeutic agents such as anti-inflammatory compounds that block local invasion/activation of monocytes, thus preventing the secretion of growth factors that may trigger vascular smooth muscle cell proliferation and migration. Other potentially anti-restenotic compounds, including antiproliferative agents, may also be administered. Other classes of drugs such as anti-thrombotics, anti-oxidants, platelet aggregation inhibitors and cytostatic agents have also been suggested for anti-restenotic use.

Drug-eluting stents may be coated with a polymeric material which, in turn, is impregnated with a drug or a combination of drugs. Once the stent is implanted at a target location, the drug is released from the polymer for treatment of the local tissues. The drug is released by a process of diffusion through the polymer layer for biostable polymers, and/or as the polymer material degrades for biodegradable polymers.

Controlling the rate of elution of a drug from the drug impregnated polymeric material is generally based on the properties of the polymer material. However, at the conclusion of the elution process, the remaining polymer material in some instances has been linked to an adverse reaction with the vessel, possibly causing a small but dangerous clot to form. Further, drug impregnated polymer coatings on exposed surfaces of medical devices may flake off or otherwise be damaged during delivery, thereby preventing the drug from reaching the target site. Still further, drug impregnated polymer coatings are limited in the quantity of the drug to be delivered by the amount of a drug that the polymer coating can carry and the size of the medical devices. Controlling the rate of elution using polymer coatings is also difficult.

Stents can be manufactured from a variety of materials. These materials include, but are not limited to, metals and polymers. Both metal and polymer vascular stents have been associated with thrombosis, chronic inflammation at the implantation site, and impaired remodeling at the stent site. It has been proposed that limiting the exposure of the vessel to the stent to the immediate intervention period would reduce late thrombosis chronic inflammation and allow the vessel to return to its normal functional state. One means to produce a temporary stent is to implant a bioabsorbable or biodegradable stent.

There are several parameters to consider in the selection of a bioabsorbable material for stent manufacture. These include, but are not limited to, the strength of the material to avoid potential immediate recoil of the vessel, the rate of degradation and corrosion, and biocompatibility with the vessel wall. Additionally, it may be desirable to include therapeutic agents in the bioabsorbable stent such that the therapeutic agent is released at the implantation site during degradation of the stent. The mechanical properties of the stent and release profiles of therapeutic agents directly depend on the rate of degradation of the stent material which is controlled by selection of the stent materials, passivation agents and the manufacturing process of the stent. Currently there are two types of materials, i.e. polymers and metals, used in bioabsorbable stents.

Bioabsorbable polymer stent materials have several significant limitations. Their radial strength is lower than metallic materials, which can result in early recoil post implantation and other mechanical tradeoffs. Also, bioabsorbable polymer stent materials are associated with a significant degree of local inflammation, and they have a relatively slow bioabsorption rate. Additionally, polymeric stents are often radiolucent which impairs accurate positioning within a vessel lumen. The physical limitations of the polymer require thick struts to increase radial strength which impedes their profile and delivery capabilities. Non-biodegradable markers are also needed to provide radiopacity. Metal bioabsorbable stents are attractive since they have the potential to perform similarly to durable metal stents.

There exists a need for a bioabsorbable, drug-eluting stent that incorporates the strength characteristics of a metal with nonpolymer drug eluting properties.

SUMMARY

According to an aspect of the invention, there is provided a method for manufacturing a stent. The method includes forming a stent blank from a first material. The stent blank includes a plurality of struts and a plurality of crowns, each crown connecting at least two struts, and a plurality of slots in at least some of the plurality of struts and/or the plurality of crowns. The method includes depositing a second material over outer surfaces of the struts and the crowns and in the slots to encase the stent blank in the second material, creating an opening through the second material, and removing the first material to form a stent comprising the second material, the stent having a continuous lumen from one end of the stent to the other end of the stent, the continuous lumen being partitioned in portions corresponding to the locations of the slots in the stent blank.

In an embodiment, forming the stent blank includes laser cutting a cylindrical substrate that includes the first material to create a pattern comprising the struts and the crowns. In an embodiment, forming the stent blank includes etching a cylindrical substrate that includes the first material to create a pattern comprising the struts and the crowns.

In an embodiment, forming the stent blank further includes laser cutting the plurality of slots. In an embodiment, forming the stent blank further includes etching the plurality of slots.

In an embodiment, the method further includes cleaning the stent blank prior to depositing the second material.

In an embodiment, the depositing includes electron deposition of the second material onto the outer surfaces of the struts and the crowns and in the slots. In an embodiment, the depositing includes electrochemical deposition of the second material onto the outer surfaces of the struts and the crowns and in the slots. In an embodiment, the depositing includes sputter coating the second material onto the outer surfaces of the struts and the crowns and in the slots.

In an embodiment, the depositing includes depositing the second material over the outer surfaces of the struts and the crowns and in the slots to create a coating having a thickness of 10-30 μm. In an embodiment, the depositing includes depositing the second material over the outer surfaces of the struts and the crowns to create a coating having a thickness of at least one-half the width of the slots.

In an embodiment, the first material includes tantalum. In an embodiment, the second material includes iron.

In an embodiment, the method includes depositing a third material over at least the outer surfaces of the struts and the crowns, the third material being radiopaque. In an embodiment, the third material comprises platinum.

In an embodiment, the method includes filling the lumen with a therapeutic substance.

According to an aspect of the invention, a stent is manufactured by a method that includes forming a stent blank from a first material. The stent blank includes a plurality of struts and a plurality of crowns, each crown connecting at least two struts, and a plurality of slots in at least some of the plurality of struts and/or the plurality of crowns. The method includes depositing a second material over outer surfaces of the struts and the crowns and in the slots to encase the stent blank in the second material, creating an opening through the second material; and removing the first material to form a stent comprising the second material and having a continuous lumen from one end of the stent to the other end of the stent.

According to an aspect of the invention, a stent is manufactured by a method that includes forming a stent blank from a first material. The stent blank includes a plurality of struts and a plurality of crowns, each crown connecting at least two struts, and a plurality of slots in at least some of the plurality of struts and/or the plurality of crowns. The method includes depositing a second material over outer surfaces of the struts and the crowns and in the slots to encase the stent blank in the second material, creating an opening through the second material, removing the first material to form a stent comprising the second material and having a continuous lumen from one end of the stent to the other end of the stent, and filling the lumen with a therapeutic substance.

BRIEF DESCRIPTION OF DRAWINGS

The foregoing and other features and advantages of the invention be apparent from the following description of the invention as illustrated in the accompanying drawings. The accompanying drawings, which are incorporated herein and form a part of the specification, further serve to explain the principles of the invention and to enable a person skilled in the pertinent art to make and use the invention. The drawings are not to scale.

FIG. **1** illustrates a stent in accordance with an embodiment of the invention that has been made by a manufacturing method according to an embodiment of the invention;

FIG. **2** illustrates a cylindrical substrate comprising a first material from which a stent blank is formed, in according with an embodiment of the invention;

FIG. **3** illustrates a stent blank that has been formed from the cylindrical substrate of FIG. **2**, in accordance with an embodiment of the invention;

FIG. **4** is a micrograph of a portion of the stent blank of FIG. **3**;

FIG. **5** is a micrograph of the portion of the stent blank with slots, in accordance with an embodiment of the invention;

FIG. **6** illustrates a portion of the stent blank of FIG. **5**;

FIG. **6**A illustrates a cross-section of the portion of the stent blank illustrated in FIG. **6**, taken along line **6**A-**6**A;

FIG. **6**B illustrates a cross-section of the portion of the stent blank illustrated in FIG. **6**, taken along line **6**B-**6**B;

FIG. **7** illustrates a cross-section of the portion of the stent blank illustrated in FIG. **6**, after a second material has been deposited on the outer surfaces of the stent blank and in the slots of the stent blank, in accordance with an embodiment of the invention;

FIG. **7**A illustrates a cross-section of the portion of the coated stent blank illustrated in FIG. **7**, taken along line **7**A-**7**A;

FIG. **7**B illustrates a cross-section of the portion of the coated stent blank illustrated in FIG. **7**, taken along line **7**B-**7**B;

FIG. **8**A illustrates the cross-section of the portion of the coated stent blank illustrated in FIG. **7**A after openings through the second material have been created, in accordance with an embodiment of the invention;

FIG. **8**B illustrates the cross-section of the portion of the coated stent blank illustrated in FIG. **7**B after an opening through the second material has been created, in accordance with an embodiment of the invention;

FIG. **9**A illustrates the cross-section of the portion of the coated stent blank illustrated in FIG. **8**A after the first material of the stent blank has been removed through the openings, in accordance with an embodiment of the invention;

FIG. **9**B illustrates the cross-section of the portion of the coated stent blank illustrated in FIG. **8**B after the first material of the stent blank has been removed through the opening, in accordance with an embodiment of the invention;

FIG. **10**A illustrates the cross-section of the portion of the stent corresponding to FIG. **9**A after a therapeutic agent has been introduced into a partitioned lumen that was created upon removal of the first material, in accordance with an embodiment of the invention; and

FIG. **10**B illustrates the cross-section of the portion of the stent corresponding to FIG. **9**B after the therapeutic agent has been introduced into the lumen that was created upon removal of the first material, in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

Specific embodiments of the present invention are now described with reference to the figures, where like reference numbers indicate identical or functionally similar elements.

FIG. **1** illustrates a stent **10** that has been manufactured in accordance with embodiments of the present invention. As illustrated in FIG. **1**, the stent **10** includes a plurality of struts **12** or substantially straight portions, and a plurality of crowns **14** or bends. Each crown **14** connects at least two struts **12**. The stent **10** includes a plurality of bands **20** or rings, each of which is comprised of a plurality of struts **12** and a plurality of crowns **14** that are connected to form a continuous band **20** centered on a longitudinal axis LA of the stent **10**. Each band **20** may be connected to an adjacent band **20** with a connector **16** that extends from a crown **14** of one band **20** to a crown **14** of an adjacent band **20**. In an embodiment, the connectors **16** may be used to connect struts **12** of adjacent bands **20**. The connectors **16** may be substantially straight, like a strut, or may be curved.

As discussed in further detail below, the stent **10** includes a substance, such as a therapeutic substance or agent, disposed within a pair of parallel lumens, and a plurality of openings **18** in at least some of the plurality of struts **12** and/or plurality of crowns **14**. More or less openings **18** may be provided. In an embodiment, the openings **18** may also be provided in at least some of the connectors **16**. The illustrated embodiment is not intended to be limiting in any way.

Methods for manufacturing the stent **10** according to embodiments of the present inventions will now be described. In an embodiment, a stent blank **100**, such as the stent blank **100** illustrated in FIG. **3**, may be formed from a cylindrical substrate **110**, illustrated in FIG. **2**, made from a first material **111**. The cylindrical substrate **110** may be a tube or a thin plate of the first material and rolled into a tube. The first material **111** may be, for example, tantalum, tungsten, molybdenum, carbon, aluminum, silver, or copper. The cylindrical substrate **110** may be laser cut to create the desired pattern of struts **112**, crowns **114**, and connectors **116** to form the stent blank **100**. FIG. **4** is a microphotograph illustrating the struts **112**, crowns **114**, and connectors **116** after the desired pattern of struts, crowns, and connectors have been formed.

In another embodiment, a cylindrical wire may be shaped into a sinusoidal waveform and wrapped around a cylindrical mandrel to form the stent blank. The wire may then be flattened against the mandrel by techniques, such as swaging. In an embodiment, the wire may have a different cross-section, such as rectangular or square. Connectors between selected crowns from adjacent wraps may be created by fusion or welding techniques.

As part of the same process, or subsequent to the process of forming the desired pattern of struts, crowns, and connectors. A plurality of slots **118** may also be formed in at least some of the struts **112** and/or crowns **114** and/or connectors **116**, as illustrated in FIG. **5**. For example, in an embodiment, the same laser may be used to cut the slots **118** into the struts **112**, crowns **114**, and connectors **116** at the same time the struts **112**, crowns **114**, and connectors **116** are cut. In an embodiment, the slots **118** may be formed at a time after the original stent blank pattern is formed. If the slots **118** are formed at a later time, the slots **118** may be cut by the same or a different laser, or the slots **118** may be etched or micro-etched from the desired struts **112**, crowns **114**, and/or connectors **116**.

In another embodiment, the desired pattern of struts **112**, crowns **114**, and connectors **116**, may be created from the cylindrical substrate **110** by etching. At the same time, the slots **118** may also be created by etching or micro-etching the cylindrical substrate **110**. In an embodiment, the slots **118** may be formed at a later time and be etched or micro-etched, or may be cut out of the desired struts **112**, crowns **114**, and/or connectors **116** by a laser.

In another embodiment, the stent blank **100** and its desired pattern of struts **112**, crowns **114**, connectors **116**, and slots **118** may be formed by three-dimensional ("3-D") printing techniques.

After the stent blank **100** having the desired pattern of struts **112**, crowns **114**, connectors **116**, and slots **118** has been formed, as illustrated in FIG. **5**, the stent blank **100** may be cleaned with an acid, or by electropolishing, or by mechanical means to remove any sharp edges, burrs and/or surface defects and provide a smooth surface. FIG. **6** illustrates a portion of the stent blank **100** after the slots **118** have been formed and the stent blank **100** has been cleaned. In the embodiment illustrated in FIG. **6**, a strut **112*a*** includes a slot **118*a*** in a center portion thereof such that a longitudinal axis of the strut **112*a*** and the longitudinal axis of the slot **118*a*** are substantially aligned. A cross-section of the strut **112*a*** along line **6**A-**6**A is illustrated in FIG. **6**A, and a cross-section of the strut **112*a*** along line **6**B-**6**B is illustrated in FIG. **6**B.

After the stent blank **100** has been cleaned, a second material **121** may then be deposited over the outer surfaces of the stent blank **100** and into the slots **118** so as to encase, i.e. completely surround and envelope, the stent blank **100**. The second material **121** may be a material known to be bioabsorbable, such as iron, magnesium, zinc, alloys of iron, alloys of magnesium, and alloys of zinc. In an embodiment, a third material may be mixed or alloyed with the second material **121** or may be deposited onto at least some of the outer surfaces of the stent blank **100** or in the slots **118** prior to the deposition of the second material **121**. For example, in an embodiment, the third material may be radiopaque and may comprise, for example, platinum.

Various methods may be used to deposit the second material **121** over the first material **111** of the stent blank **100**. For example, in an embodiment, electron deposition may be used to deposit the second material **121** over the outer surfaces and into the slots **118** of the stent blank **100**. In an embodiment, the second material **121** may be sputter coated over the outer surfaces and into the slots **118** of the stent blank **100**. Other coating techniques, such as electrodeposition, chemical vapor deposition (CVD), or plasma-enhanced chemical vapor deposition (PECVD) may be used to coat the second material **121** onto surfaces of the first material **111**. In an embodiment, the second material **121** may be deposited so that it forms a coating having a thickness of 10-30 μm over the stent blank **100**. In an embodiment, the thickness may be about 25 μm. In an embodiment, the second material **121** may be deposited over the outer surfaces of the stent blank **100** to create a coating having a thickness of at least one-half the width of the slots **118**. In an embodiment, the second material **121** may be deposited over the outer surfaces of the stent blank **100** to create a coating having a thickness of equal to or less than one-half the width of the slots **118**.

FIG. **7** illustrates the same portion of the strut **112*a*** illustrated in FIG. **6** after the stent blank has been encased in the second material **121**. A cross-section of the strut **112*a*** and the second material **121** along line **7**A-**7**A is illustrated in FIG. **7**A, and a cross-section of the strut **112*a*** and the second material **121** along line **7**B-**7**B is illustrated in FIG. **7**B.

Openings **120** may be created through the second material **121** so as to expose the first material **111**, as illustrated in FIGS. **8**A and **8**B. The first material **111** may then be removed, for example, by chemical etching, or other methods. The removal of the first material **111**, which is a sacrificial material, is accomplished without damaging the struts **12**, crowns **14**, or connectors **16**. For example, and not by way of limitation, if the first material **111** is copper or silver, it may be removed using nitric acid. Phosphoric acid mixtures may be used to remove aluminum. Gas or plasma etching may be used to remove tungsten, molybdenum, tantalum or carbon.

Various materials may be used for the first material **111**, and various materials may be used for the second material **121**. The materials and etchants are selected such that the etchants dissolve or otherwise remove the first material **111** without damaging the second material **121**. U.S. patent application Ser. No. 12/500,359, filed Jul. 9, 2009, and published as U.S. 2011/0008405 on Jan. 13, 2011, incorporated herein in its entirety by reference, discloses various etchants that remove one metal or alloy without damaging another metal or alloy.

Upon removal of the first material **111**, the second material **121** remains as the struts **12**, crowns **14**, and connectors **16** of the stent **10**, and the stent **10** has a continuous lumen **122** from one end of the stent **10** to the other end of the stent **10**, as illustrated, for example, in FIGS. **9**A and **9**B. For the portions of the stent **10** that corresponded to the portions of the stent blank **100** that included slots **118**, the lumen **122** remains continuous, but is partitioned with a strengthening member **124** comprised of the second material **121** that was previously deposited into the slots **118** in the center of the lumen **122**, as illustrated in FIG. **9**A. For example, for the portion of the strut **12** that corresponds to the portion of the strut **112***a* of the stent blank illustrated in FIG. **6**, the strengthening member **124** is oriented parallel with the strut **12** and does not create any discontinuity within the lumen **122** so that the lumen remains continuous from one end of the stent **10** to the other end of the stent **10**.

If the stent **10** is a drug-eluting stent, the continuous lumen **122** may then be filled with an adjunctive or therapeutic substance **126**, as illustrated in FIGS. **10**A and **10**B. The lumen **122** may be filled through the openings **120** and/or other openings created for the purpose of filling the lumen **122**. Such additional openings, if used, may then be closed after the lumen **122** is filled with the adjunctive or therapeutic substance **126**. The lumen **122** is filled with the adjunctive or therapeutic substance by various methods. For example, a liquid or semi-liquid state of the adjunctive or therapeutic substance may be introduced into the lumen **122** by one or more methods described in U.S. patent application Ser. No. 13/457,398, filed Apr. 27, 2012, published as United States Patent Application Publication No. 2013/0284310 on Oct. 31, 2013 and entitled "Apparatus and Methods for Filling a Drug Eluting Medical Device Via Capillary Action", and in U.S. patent application Ser. No. 13/457,418, filed Apr. 27, 2012, published as United States Patent Application Publication No. 2013/0284311 on Oct. 31, 2013 and entitled "Apparatus and Methods for Filling a Drug Eluting Medical Device Via Capillary Action", both of which are incorporated herein by reference in their entireties. In an embodiment, the lumen **122** may be filled with a suitable visopaque or iodine/dense metal solvent to increase the radiopacity of the stent **10** while the stent **10** is being implanted in a vessel, but then vanishes with dissolution. In an embodiment, the lumen may be filled with combinations of substances that increase the radiopacity of the stent while the stent is being implanted in a vessel and also provide a therapeutic effect to the vessel after the stent is implanted in the vessel.

It would be understood by those of ordinary skill in the art that the openings **120** may be located at various locations along the struts **12** and crowns **14**. The size, shape, and/or density (number per unit length or area) of the openings **120** may be varied along the stent **10**. Such variations may alter the elution rate of the adjunctive or therapeutic substance along the stent **10**. For example, and not by way of limitation, more or larger openings may be providing in the middle portion of the stent **10** and less or smaller openings may be provided near the ends of the stent **10**.

To determine the beneficial effect of having a partitioned lumen within a strut, crown, or connector, finite element analysis (FEA) was completed for various cross-sections of a strut made from iron (Fe). Based on literature, the mechanical properties of iron were estimated to be 211 GPa for the Young's Modulus, 300 MPa for the Yield Stress, 135 MPa for the Plastic Modulus, and 0.29 for Poisson's Ratio. Four single strut models were completed using FEA software, and the characteristics of the struts and the predicted strength results, are listed in Table I:

TABLE I

Modeling Results				
	Model 1 Solid Strut	Model 2 Single Lumen	Model 3 Single Lumen	Model 4 Partitioned Lumen
Strut Volume (mm^3)	0.02	0.02	0.025	0.025
Mass (mg)	0.16	0.11	0.12	0.16
Surface Area (mm^2)	0.7	1.09	1.22	1.44
Strength (mN)	42	35	53	63

The modeling results indicate that with a constant material and contour geometry, i.e. constant segment length and deployment angles, the strength of the strut may be increased by increasing the thickness/volume of the strut. In addition, the strength of the strut may be increased by hollowing out the strut, i.e. providing a lumen or lumens in the strut, and increasing the volume of the strut. The Model **1** strut, which is solid in cross-section, but thinner than the struts of Models **3** and **4**, is predicted to have a strength of 42 mN, while the Model **3** strut, which contains a single lumen, but is thicker than the struts of Models **1** and **2**, is predicted to have a strength of 53 mN. Further increasing the strength of the strut cannot be done by making the lumen larger, without lowering the surface area or increasing the volume of the strut. The Model **4** strut, which includes a partitioned lumen, has the same mass as, but greater surface area than, the Model **1** solid strut, and a greater mass and surface area than the Model **3** strut, and is predicted to have a strength of 63 mN, which is higher than the predicted strength of the other Models.

Embodiments of the present invention provide a stent having an enhanced internal three-dimensional geometry that includes a continuous lumen from one end of the stent to the other end of the stent, and portions of the stent in which the lumen is partitioned with strengthening members in the partitioned portion of the lumen. It may be desirable to locate a partitioned lumen with a strengthening member in at least 30% of a curved section, i.e. crown, and/or areas of potential or anticipated high strain, and/or transition areas between straight and curved sections, i.e. between struts and crowns, or multi-curved sections. Although the illustrated embodiment depicts a strengthening member that resembles an I-beam, other shapes may be created by controlling the shape of the stent blank, including the slots.

The enhanced three-dimensional geometry may further increase the strength of the stent, without increasing the total volume of the stent material. For bioabsorbable stents, it is desirable to optimize the ratio of the surface area to volume to minimize the overall degradation time. For example, although iron is known to have good strength and mechanical properties, iron has a relatively slow degradation rate. By forming the stent in accordance to embodiments of the present invention, an improved bioabsorbable, drug-eluting stent with good mechanical properties and short degradation times may be provided.

The stent **10** may be used conventionally in blood vessels of the body to support such a vessel after an angioplasty procedure. It is known that certain drugs eluted from stents may prevent restenosis or other complications associated with angioplasty or stents. The stent **10** may alternatively be used in other organs or tissues of the body for delivery of drugs to treat tumors, inflammation, erectile dysfunction, nervous conditions, or other conditions that would be apparent to those skilled in the art.

The therapeutic substance or drug **126** may include, but is not limited to, antineoplastic, antimitotic, antiinflammatory, antiplatelet, anticoagulant, antifibrin, antithrombin, antiproliferative, antibiotic, antioxidant, and antiallergic substances as well as combinations thereof. Examples of such antineoplastics and/or antimitotics include paclitaxel (e.g., TAXOL® by Bristol-Myers Squibb Co., Stamford, Conn.), docetaxel (e.g., TAXOTERE® from Aventis S. A., Frankfurt, Germany), methotrexate, azathioprine, vincristine, vinblastine, fluorouracil, doxorubicin hydrochloride (e.g., ADRIAMYCIN® from Pharmacia & Upjohn, Peapack N.J.), and mitomycin (e.g., MUTAMYCIN® from Bristol-Myers Squibb Co., Stamford, Conn.). Examples of such antiplatelets, anticoagulants, antifibrin, and antithrombins include sodium heparin, low molecular weight heparins, heparinoids, hirudin, argatroban, forskolin, vapiprost, prostacyclin and prostacyclin analogues, dextran, D-phe-pro-arg-chloromethylketone (synthetic antithrombin), dipyridamole, glycoprotein IIb/IIIa platelet membrane receptor antagonist antibody, recombinant hirudin, and thrombin inhibitors such as ANGIOMAX™ (Biogen, Inc., Cambridge, Mass.). Examples of such cytostatic or antiproliferative agents include ABT-578 (a synthetic analog of rapamycin), rapamycin (sirolimus), zotarolimus, everolimus, angiopeptin, angiotensin converting enzyme inhibitors such as captopril (e.g., CAPOTEN® and CAPOZIDE® from Bristol-Myers Squibb Co., Stamford, Conn.), cilazapril or lisinopril (e.g., PRINIVIL® and PRINZIDE® from Merck & Co., Inc., Whitehouse Station, N.J.), calcium channel blockers (such as nifedipine), colchicine, fibroblast growth factor (FGF) antagonists, fish oil (omega 3-fatty acid), histamine antagonists, lovastatin (an inhibitor of HMG-CoA reductase, a cholesterol lowering drug, brand name MEVACOR® from Merck & Co., Inc., Whitehouse Station, N.J.), monoclonal antibodies (such as those specific for Platelet-Derived Growth Factor (PDGF) receptors), nitroprusside, phosphodiesterase inhibitors, prostaglandin inhibitors, suramin, serotonin blockers, steroids, thioprotease inhibitors, triazolopyrimidine (a PDGF antagonist), and nitric oxide. An example of an antiallergic agent is permirolast potassium. Other therapeutic substances or agents that may be used include nitric oxide, alpha-interferon, genetically engineered epithelial cells, and dexamethasone. In other examples, the therapeutic substance is a radioactive isotope for implantable device usage in radiotherapeutic procedures. Examples of radioactive isotopes include, but are not limited to phosphorus (P^{32}), palladium (Pd^{103}), cesium (Cs^{131}), Iridium (Ir^{192}) and iodine (I^{125}). The substances or agents are provided by way of example and are not meant to be limiting. Other therapeutic substances are equally applicable for use with the disclosed methods and compositions.

While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of illustration and example only, and not limitation. It will be apparent to persons skilled in the relevant art that various changes in form and detail can be made therein without departing from the spirit and scope of the invention. Thus, the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the appended claims and their equivalents. It will also be understood that each feature of each embodiment discussed herein, and of each reference cited herein, can be used in combination with the features of any other embodiment. Furthermore, there is no intention to be bound by any expressed or implied theory presented in the preceding technical field, background, brief summary or the detailed description. All patents and publications discussed herein are incorporated by reference herein in their entirety.

What is claimed is:

1. A method for manufacturing a stent, the method comprising:

forming a stent blank from a first material, the stent blank comprising a plurality of struts and a plurality of crowns, each crown connecting at least two struts;

forming a plurality of slots into at least some of the plurality of struts and/or the plurality of crowns, such that the plurality of slots extend through the first material to create openings through the at least some of the plurality of struts and/or the plurality of crowns;

depositing a second material over outer surfaces of the struts and the crowns and through the slots to encase the stent blank in the second material;

creating an opening through the second material; and

removing the first material to form a stent comprising a plurality of struts and crowns defined by the second material, a continuous lumen is defined by the plurality of struts and crowns of the second material, the continuous lumen being partitioned in portions corresponding to the locations of the slots in the stent blank.

2. The method according to claim **1**, wherein said forming the stent blank comprises laser cutting a cylindrical substrate comprising the first material to create a pattern comprising the struts and the crowns.

3. The method according to claim **2**, wherein said forming further comprises laser cutting the plurality of slots.

4. The method according to claim **2**, wherein said forming further comprises etching the plurality of slots.

5. The method according to claim **1**, wherein said forming the stent blank comprises etching a cylindrical substrate comprising the first material to create a pattern comprising the struts and the crowns.

6. The method according to claim **5**, wherein said forming further comprises etching the plurality of slots.

7. The method according to claim **5**, wherein said forming further comprises laser cutting the plurality of slots.

8. The method according to claim **1**, further comprising cleaning the stent blank prior to said depositing the second material.

9. The method according to claim **1**, wherein said depositing comprises electron deposition of the second material onto the outer surfaces of the struts and the crowns and in the slots.

10. The method according to claim **1**, wherein said depositing comprises electrochemical deposition of the second material onto the outer surfaces of the struts and the crowns and in the slots.

11. The method according to claim **1**, wherein said depositing comprises sputter coating the second material onto the outer surfaces of the struts and the crowns and in the slots.

12. The method according to claim **1**, wherein said depositing comprises depositing the second material over the outer surfaces of the struts and the crowns and in the slots to create a coating having a thickness of 10-30 μm.

13. The method according to claim **1**, wherein said deposition comprises depositing the second material over the outer surfaces of the struts and the crowns to create a coating having a thickness of at least one-half the width of the slots.

14. The method according to claim **1**, wherein the first material comprises tantalum.

15. The method according to claim **1**, wherein the second material comprises iron.

16. The method according to claim **1**, further comprising depositing a third material over at least the outer surfaces of the struts and the crowns before said depositing the second material, the third material being radiopaque.

17. The method according to claim **16**, wherein the third material comprises platinum.

18. The method according to claim **1**, further comprising filling the lumen with a therapeutic substance.

19. The method according to claim **1**, further comprising forming

the plurality of slots in a center portion of at least some of the plurality of struts, such that a longitudinal axis of a strut and a longitudinal axis of a slot are substantially aligned.

20. The method according to claim **1**, further comprising forming

the plurality of slots in at least some of the plurality of crowns, such that the shape of the slots and crowns have substantially the same curvature.

21. The method according to claim **1**, further comprising forming

the plurality of slots in at least some of the plurality of struts and/or plurality of crowns, such that the plurality of slots extend from one side of the struts and crowns through to another side of the struts and crowns.

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